

*To appear in Magnetic Fields Across the Hertzsprung-Russell Diagram  
ASP Conference Series, 2001  
Gautier Mathys, Sami K. Solanki and Dayal T. Wickramasinghe, eds.*

## Observable Effects of B fields on the Winds and Envelopes of Hot Stars

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### Abstract.

Magnetic fields on hot stars can produce a variety of interesting effects on the velocity, density, and temperature structure in the winds from the stars. The fields can produce a longitudinal dependence of the mass flux, which would lead to cyclical variability such as that seen in optical and UV spectra of many early-type stars. The fields can channel and spin-up the outflow, which appears to be needed to explain the disk-like density enhancements around Ap and Be stars. Magnetic confinement of hot gases can occur and be responsible for the anomalously high EUV fluxes seen in B giants, and the anomalous high ion X-ray line emission that is seen in recent CHANDRA observations. Special attention is given to the reports at this meeting that A stars develop magnetic Ap phenomenon only after about 30 percent of their main sequence lifetimes. A similar delay occurs for the emission line Be stars. It is suggested that these delays are related to the time it takes for fields to rise through the sub-adiabatic envelope to the surface starting from the interface between the convective-core and radiative-envelope where they are generated.

### 1. Introduction

Early type stars have several major differences from the Sun and other cool stars, and these lead to a new array of magnetic phenomena. The early type stars tend to be very luminous, and the emission line Of stars and the OB supergiants lie rather near the Eddington upper luminosity limit. Because of the strong radiation fields, the most important properties of their winds can be explained by line driven wind theory as first developed by Castor, Abbott and Klein (CAK, 1975). With the modifications of CAK theory developed by Friend & Abbott (1986) and Pauldrach, Puls, & Kudritzki (1986), we can now understand why the mass loss rates of luminous early-type stars are in the range of  $10^{-6}$  to  $10^{-5} M_{\odot} \text{ yr}^{-1}$ , and why the terminal velocities,  $v_{\infty}$ , are generally in the range of 1500 to 3000  $\text{km s}^{-1}$ . However, there are some properties of hot stars that are not easily explained by line driven wind theory, and magnetic fields appear to play a role in those. For example, in line driven wind theory, one should expect that the radiation field should be axially symmetric. There could be a latitude dependence owing to polar brightening in rapidly rotating stars, however as we have heard in the paper by Henrichs, there are dependences of the winds on longitude, and this leads to the cyclic variability in UV wind

diagnostics. The O, B, and A stars also tend to be rapid rotators. In the case of the emission line Be stars the rotation speeds are on average about 70 percent of the critical rotation speed at which the surface is rotating at Keplerian speed. These stars have equatorial disks, and a consensus has recently been reached that the disks are Keplerian (Smith, Henrichs, & Fabregat, 2000). So the major problem for understanding the Be stars is explaining how a star rotating at sub-Keplerian speed can produce a Keplerian disk. Co-rotating magnetic fields could lead to the needed transfer of mass and angular momentum from the star to the disk.

## 2. Evidence Across the Spectrum

Here I will briefly discuss the evidence for magnetic fields that are seen in early-type stars at wavelengths ranging from X-ray to the optical. The X-rays from early type stars are usually explained as arising from shocks that are distributed throughout the relatively dense winds. The recent launches of the Chandra and XMM satellites have led to a great improvement of our understanding of the source of the X-rays because of the high spectral resolution they provide. The X-rays in the winds are thought to be produced by instabilities in line driven winds. However, models for shock formation such as those by Lucy (1982) and Feldmeier et al (1997) and others have consistently failed to predict the high level of X-ray emission in the brightest stars such as  $\zeta$  Pup (O4f) (Cassinelli et al 2001, Kahn et al; 2001) and  $\zeta$  Ori (O9.5 Ia) (Cassinelli and Swank, 1983, Waldron & Cassinelli, 2001). The X-ray spectral lines allow us for the first time to determine the radius at which the X-rays are originating. In the case of the two stars mentioned, there is evidence that X-rays from the highest ion stages are originating so close to the star that the local wind and its maximal strength shocks could not produce the high ion stages such as Si XIII and S XV that are observed. Waldron & Cassinelli (2001) and Schulz et al (2000) in particular, have suggested that magnetic fields are largely responsible for the very hot gases. In the case of lower luminosity near-main sequence B stars, Cohen et al (1997) found that the X-ray luminosities are larger than could be generated by the emission measure of the entire wind. This also suggests that there could be an extra source of X-ray emitting material that is perhaps magnetically confined.

There is also indirect evidence for magnetic fields in stars observable in the extreme ultraviolet. Only two early-type stars  $\epsilon$  CMa (B2 II) and  $\beta$  CMa (B1 II-III) could be observed with the EUVE satellite. These two stars lie in a rarefied tunnel in the ISM and the attenuation of their EUV light is unusually small. For  $\epsilon$  CMa, Cassinelli et al. (1995) found the star to have a photospheric radiation flux level in the wavelength range 500 to 700 Å that exceeds the values predicted by model atmospheres by a factor of about 30. This excess could be produced if the star were to have an outer atmospheric zone like a chromosphere, that is hotter than expected from radiative equilibrium model predictions. Such a zone is present in the solar atmosphere, but is not otherwise observed in O and B stars; nor is one expected since hot stars do not have an outer convection zone. Thus, some sort of mechanical heating seems to be required. A possible explanation is provided by observations of the other EUVE stellar source,  $\beta$  CMa. This star shows an EUV continuum flux that exceeds model predictions by about a factor

of 5 (Cassinelli et al. 1996). It is a bright pulsating variable of the  $\beta$  Cephei class, and the star  $\beta$  Cephei itself has been measured via the Zeeman effect methods to be an oblique rotator with a field of about 100 Gauss (Henrichs et al. 2001, and at this meeting). The connection between the heating that is needed on one bright member of this class of variables, and the magnetic field that is seen on another is not yet clear, but the possibility that a magnetic field is also present on  $\beta$  CMa is plausible and very interesting. The results might mean that heated outer atmospheres are common among B stars.

In the ultraviolet, there are very many observations of hot star spectra. Perhaps of most interest here are the observations of cyclic behavior of the discrete absorption components (DAC's) of moderately strong UV resonance line profiles (Prinja et al. 1992; Kaper et al. 1996). The progression of the DAC features across the line profiles has been explained by the co-rotating interaction region (CIR) model of Cranmer and Owocki (1996). CIR's are present in the solar wind, and Mullan (1984) had proposed that they are present also in hot star winds. What is needed in the model, are sectors of fast stellar wind streams adjacent to sectors of slower moving material. This is not expected to occur in purely radiation driven winds. However, it is well known in solar work that magnetic fields can lead to fast stream - slow stream outflow. MacGregor (1988) investigated a way in which this could occur on a star with a line driven wind by magnetic channeling of the flow, and Cassinelli and Miller (1999) have suggested that there could be sectors of faster wind driven by luminous magnetic rotator forces.

In the optical, a correlation has been found by Henrichs et al. (1998) between the  $H\alpha$  emission line variability and the wind UV lines. This links the DAC phenomena, discussed above, to something occurring at or near the surface of the stars. The  $H\alpha$  double peaked lines are the best studied diagnostic of the Be star disks. In recent years, monitoring of the variations of the violet (V) and red (R) peaks in the  $H\alpha$  lines has shown that there is a quasi cyclical change in the V and R components of the line on time scales of a few years, (Hanuschik et al. 1995). This has been explained with models for a one-armed spiral pattern or a "global disk oscillation" in the equatorial disk around the stars (Okazaki, 1991, 1997; Papaloizou et al. 1992). For such a pattern to develop, the matter must have a long residence time in the disk. This would not be expected in the "wind compressed disk" (WCD) model of Be stars by Bjorkman and Cassinelli (1993) that led to explanations of large equatorial density enhancements and to the IR excess and intrinsic polarization of the Be stars. In the WCD model matter from the star flows towards, and shocks at, the equatorial region as a natural consequence of equator-crossing trajectories of a wind flowing from a rapidly rotating star. However, a WCD has matter continuing to flow outwards in the equatorial plane, and would not produce the one armed spiral behavior. To achieve the large angular velocities of a Keplerian disk, the star must transmit not only mass but also angular momentum to its wind. This can be achieved by having the flow channeled by a co-rotating magnetic field.

### 3. The General Dynamical Effects of B fields on Hot star Winds

The fast rotation of hot stars leads to the most prominent effects that connect fields with the hot star outflows. Here several aspects are considered. A topic which I call Luminous Magnetic Rotator theory was developed by Friend & MacGregor (1984), and applied to Wolf Rayet stars by Poe, Friend & Cassinelli (1987). It is a combination of the well know Weber and Davis (1967) model for the solar wind, with line driven wind theory of CAK. From the perspective of the basic Weber and Davis model, there is a primary mechanism for driving an outflow, and it is amplified by the effects of the magnetic field. The primary mechanism for the solar wind would be combination of effects that could be called the coronal mechanism, for hot stars the primary mechanism would be the CAK wind theory. The addition of a field can lead to the star being a slow, fast, or centrifugal, magnetic rotator. The Sun is an example of a slow magnetic rotator because the rotation of the field does not lead to a significant increase in the wind speed. Fast Magnetic Rotator theory as explained by Hartmann and Macgregor (1980) can lead to a fast equatorial outflow, which could be important in the production of the co-rotating interaction regions discussed above. In the centrifugal magnetic rotators the sub-sonic region is rotating at roughly solid body rotation with the star and this enhances the density at the critical point and leads to an increased mass loss rate. Also along this sequence of magnetic rotators is an increase in the angular momentum transferred from the star to the wind. It is the angular momentum addition that makes it possible to explain the formation of disks around stars.

An oblique rotator structure for the magnetic field is a particularly well studied variant of the magnetic rotator theory. Shore (1999) has shown that the B fields in oblique rotators give rise to a periodic and directed wind that explains the outflows observed in B chemically peculiar stars. It is this picture of a significant flow from the oblique rotating wind that is supported by the time variations of the Zeeman effect that has been reported by Henrichs et al. (2001). The theoretical picture for disk formation around an oblique rotator has been developed for the Ap stars by Babel and Montmerle (1997). It was used several times during this meeting to explain the observed cyclical variability of Ap stars.

In the formation of planetary nebulae, the magnetic fields have been used to explain the bipolar outflows that are commonly seen. These models are commonly called Magnetic Wind Blown Bubbles and the theory has been developed by Chevalier and Luo (1994), García-Segura et al. (1999) and others.

### 4. Timescales

In hearing the talks on early- type stars at this meeting, it occurred to me that there are some interesting stellar aging effects in hot stars that might be explainable in a straightforward way.

We have heard from Mathys that among the A-stars, the Ap phenomenon does not occur for the first 30 percent of the lives of the stars. Similarly, at the recent IAU Coll. 175 meeting on Be stars, Capilla, Fabregat & Baines, (2000) and others reported that Be stars are not found in clusters that are younger

than about  $10^7$  years, i.e. there is a delay time of about 10 - 30 percent of the life of a B stars before disks become an important feature. So both types of magnetically induced phenomena appear to have a delay of order 10 percent of the stellar life before they can occur. Stretching further to the O-stars we find from Wood & Churchwell (1989) that the stars are hidden from view for the first 10 percent of their main-sequence lifetimes. The first evidence of the O- stars are Ultra Compact HII regions, which often show very massive bi-polar outflow which seem to me to be caused by magnetic rotator forces. Churchwell (1997) tabulates several such O-stars in which the mass in the bipolar outflow exceeds the mass of the star at the center. Only magnetic forces associated with the collapse of the cloud could produce such a situation.

Thus, there are interesting magnetic phenomena occurring in the early lives of O, B, and A stars. In the case of the B and A stars, we can certainly ask what could cause the delay the start of the Be and Ap phenomena.

The time scales involved are very similar to the times mentioned in the talk by Charbonneau. He showed results from the calculations of MacGregor and Cassinelli (2001) for the rise of magnetic fields through the sub-adiabatic envelopes of hot stars. For the calculation, a torus of flux that is similar to those used in modeling the rise of magnetic fields in the Sun is considered. Assuming an initial pressure and temperature balance between the flux tube and the external medium, there is an initial buoyant force that causes the field region rise. However being in a sub-adiabatic region the rising tube finds itself cooler than the surroundings and has a tendency to stop its rise. It continues to rise at a terminal rate that is set by heating of the tube by the somewhat hotter ambient medium. This leads to a rise of the flux tubes on a time scale comparable to roughly 30% of a lifetime delay for the onset of the Ap and Be phenomena. It seems reasonable to suggest that some sort of flux tube rise scenario could produce what we see in these two classes of stars. (A somewhat similar scenario has been proposed at this meeting for the cool star dividing line on the HR diagram, by Holzwarth, Schüssler, and Solanki). If the rise time for the flux tube controls the onset of the magnetic phenomena in Ap and Be stars, it leads us to also predict a termination of the Ap and Be phenomena for the following reason. The composition of the interface region where the field is generated is changing with time as the core becomes more enriched in helium. Thus the mean molecular weight changes by about a factor of two and this extra mass per particle could inhibit the rise of the magnetic flux tubes.

## 5. Conclusions

As a closing remark, I want to say that I have found this to be an extremely useful meeting, because it has brought together astronomers with such a wide range of range of interests and expertise. We in the hot star community have relatively few actual measurements of magnetic fields, so it has been especially beneficial to discuss and hear about magnetic mechanisms, effects and diagnostics that used in solar and cool star astronomy research. I hope that the different range in phenomena that is found in hot star astronomy will continue to attract the interest of experts in the these other fields as well.

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## Discussion

MOUSCHOVIAS: You stated that magnetic fields can reverse the infall and convert it to an outflow. Is that statement a result of a calculation or is it speculation.

CASSINELLI: No, it is not a model result. However I think the idea that an infall can be reversed has already been developed. Such a reversal is calculated to occur in the Shu's X-wind model for the formation of low mass stars. I was just suggesting that a similar thing could occur for massive stars but at a larger distance from the star because of the greater velocities and mass fluxes are involved. I made the statement because I am aware of the rate at which mass can be driven from a star by the various forces available. It would be impossible to have such a massive flow arise from the O star itself, even by the Luminous Magnetic Rotator theory, which drive the most massive of the winds we considered in Lamers and Cassinelli (1999). The flow reversal would need to occur before the matter became too deep in the stars gravitational field, and centrifugal magnetic rotator forces would seem like the most likely ones to achieve the outflow.

BERDYGINA: Be stars appear also in binaries. What will be the difference between the Be star accreting matter from the secondary and a Be star with the magnetic field without accretion.

CASSINELLI: The answer to this question has been addressed by Geis (2000). Yes there are some Be stars that are binaries, but it is now generally agreed that what is considered to be the "Be phenomenon" is not a mass transfer process, but arises most frequently in single stars.

SCHMITT: Assume that the X-ray emission of hot stars is from confined magnetic loops. 1) What is heating the plasma? and 2) Why is  $L_x \sim L_{bol}$ .

CASSINELLI: Even early-type stars can have sources of mechanical energy, The stars tend to be rapid rotators and the rotation is not solid body, but differential. In addition there are circulation currents occurring in the stars and non-radial pulsations. Also, in one well studied star,  $\tau$  Sco B0.5 V, there seems to be an infall of matter from the stalled wind. I certainly don't know of the mechanism that could lead to heating, but there is no lack of possibilities for sources of mechanical energy. The proportionality between  $L_x$  and  $L_{bol}$  holds approximately for the O- stars, but these have winds that are optically thick to X-rays. Most of the X-rays we detect are produced by shocks in the winds, which are produced by interactions of matter driven by the luminosity of the star. When we looked to the somewhat less luminous near main sequence stars in our ROSAT studies, which have optically thin winds, and so all of the X-rays that are produced can be seen (Cohen et al.1997), we found that  $L_x$  dropped sharply below the  $10^{-7} L_{bol}$  relation, i.e.  $L_x$  is not proportional to  $L_{bol}$ .



MOSS: The rise speed of the flux tube in a stably stratified region is proportional to  $B^2/r_T^2$ , where  $r_T$  is the tube radius and  $B$  the field strength. I estimate (see my paper) that for  $t_{rise} \sim 10^8$  years,  $r_T \sim 10^{-3} R_*$  for Ap star parameters. Thus the field rises as “spaghetti”, but must become organized at the surface to present the large scale (ordered) poloidal field. Can you comment on how this might occur?

CASSINELLI: In the simple picture of flux tubes that MacGregor and I have worked on, and as described in Charbonneau’s talk, it is difficult to picture how there could be the communication between the northern and southern hemispheres of the star needed for the global poloidal structure. Perhaps the rising flux tubes are primarily contributing to the quadrupolar and other higher order components that we have learned here are on present on Ap stars.

RUEDIGER: If the Ap stars are an old population among the A stars, also their slow rotation must suddenly appear during the main-sequence evolution. Or is the slow rotation of the Ap stars already present at the ZAMS, without stellar magnetism and peculiar chemistry?

CASSINELLI: I wouldn’t say that the delay of 10 to 30 would make the Ap stars an old population. But more to the point I do not see that the slow rotation and the chemical peculiarity have to appear simultaneously during the main sequence evolution. The diffusion of the elements in Ap stars could be affected either by the presence of a dipole or by higher the more localized fields associated with the rise of flux tubes.